

## Single Helicity States in Reversed Field Pinches

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**T**he Reversed Field Pinch (RFP), like the tokamak and the stellarator, belongs to the family of toroidal devices for fusion energy where a toroidal plasma is magnetically confined. However, the RFP differs from a tokamak in several aspects [1]. First, the toroidal and poloidal magnetic fields are of the same order, mainly generated by currents inside the plasma. Second, the poloidal currents in the plasma are sustained by a dynamo mechanism. Third, the toroidal magnetic field becomes negative at the edge of the plasma such that the safety factor profile  $q$  (winding number of field lines) is a decreasing function of radius, starting typically from  $q(r=0) \sim 0.1$  and reversing sign at the edge. For this reason, the RFP is subject to several magnetohydrodynamic (MHD) instabilities with poloidal mode number  $m = 1$  and various toroidal mode number  $n$  (depending of the aspect ratio  $R/a$  of the machine, where  $R$  and  $a$  are the major and minor radius of the torus, respectively).

For several decades the RFP has been considered a device with bad plasma confinement properties, characterized by a turbulent state with magnetic field line chaos. This state, characterized by a wide spectrum of modes fluctuating with similar amplitudes, is known as the multiple helicity state. However, recent experimental results (motivated by numerical simulations of the early nineties [2]) have shown a new paradigm for the RFP: under certain conditions, the plasma can achieve the so-called quasi-single helicity state, namely a state where the mode spectrum is dominated by a  $(m = 1, n = n_0)$  mode while the other modes are fluctuating at much smaller amplitude [3]. The quasi-single helicity state has been observed in several experiments (with fairly different

characteristics) throughout the world such that this result is now considered very solid. More important, the quasi-single helicity state is characterized by improved flux surfaces and less magnetic chaos and turbulence, which mean better confinement properties.

It is worth mentioning at this point that the RFP with strong improvement of the plasma confinement can be really interesting for fusion applications. In fact, RFPs do not require the toroidal field coils to be superconducting (since the confinement field is produced mainly by the plasma), can reach high  $\beta$  (ratio of internal energy to magnetic field energy), thus reducing the amplitude of the confining field. They are also very compact and can reach thermonuclear temperatures without additional heating (due to the higher ohmic dissipation and higher currents with respect to the tokamak) [4].

Given the premise above, the work conducted within the T-15 Plasma Theory Group is devoted to understand the reasons leading to the transition from multiple helicity states to quasi-single helicity states. The task is addressed through three-dimensional visco-resistive MHD simulations with the code PIXIE3D [5]. This code has been developed in T-15 by L. Chacón. It is parallel, fully implicit, and written in curvilinear geometry such that it is possible to run it in various geometries (of particular interest for the present study are the helical, cylindrical, and toroidal geometries).

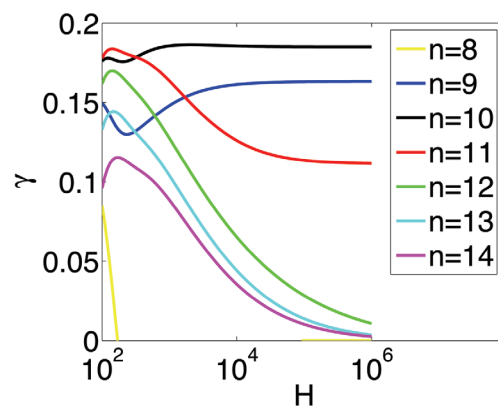
The simulations are conducted by starting from the paramagnetic pinch equilibrium. This is a cylindrical equilibrium where the axial magnetic field at the edge of the plasma is not reversed. The paramagnetic pinch is the typical choice when describing the start-up scenario of the RFP and is subject to several  $(m = 1, n)$  instabilities (see Fig. 1).

As the mode grows, the cylindrical symmetry is lost and the plasma column becomes helically distorted.

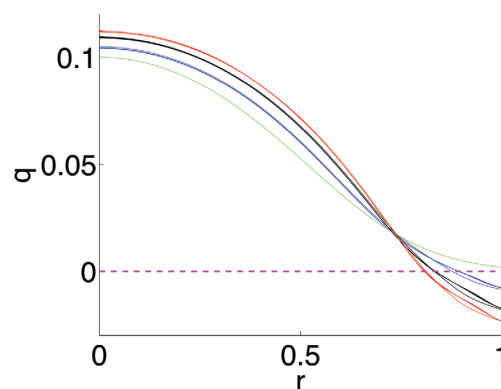
Furthermore, the toroidal magnetic field decreases at the edge and becomes reversed (and so does the safety factor profile  $q$ ). As a result of toroidal flux conservation, the mean-field  $q$  profile grows at  $r = 0$  (see Fig. 2), thus changing the position where the linearly unstable modes are resonant. The helical flux reveals a very interesting nonlinear dynamics property, in which the separatrix characteristic of the resonant mode disappears as the island grows (see Fig. 3). The final aim of the work consists in applying external forcing to the device such to have a stationary single-helicity state in the plasma over a wider range of parameters.

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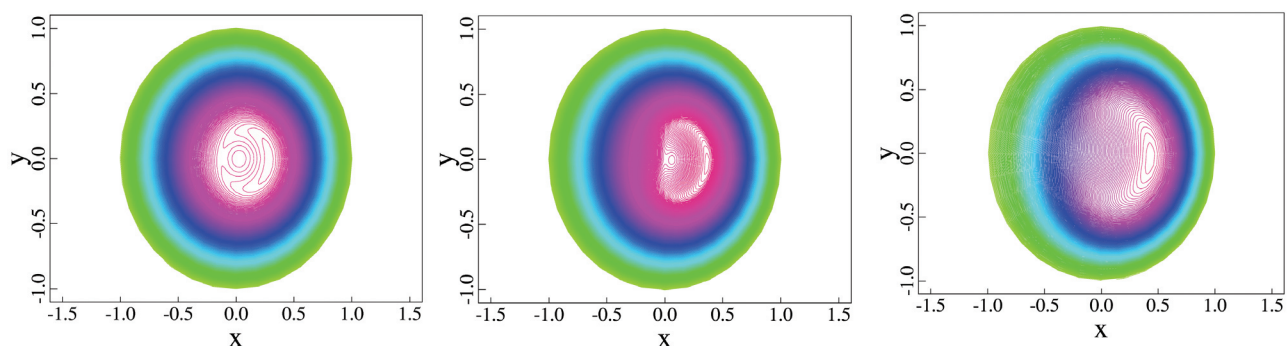
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**Fig. 1.** Stability analysis of the paramagnetic pinch. Several modes are simultaneously unstable for a wide range of Hartmann number.



**Fig. 2.** Mean-field  $q$  profile computed from the saturated state of various runs with PIX-IE3D. Only a single helicity is present: ( $m = 1$ ,  $n = 9$ ) blue, ( $m = 1$ ,  $n = 10$ ) black and ( $m = 1$ ,  $n = 11$ ) red. The green curve is obtained for the paramagnetic pinch equilibrium.



**Fig. 3.** Evolution of the helical flux for a single helicity run with ( $m = 1$ ,  $n = 11$ ).